High Bandwidth Heat Transfer Measurements in an Internal Combustion Engine under Low Load and Motored Conditions

K.S. Chana*, T.S. Wilson†
Prof. P. Bryanston-Cross†, M. Burnett†

Prof. T.V. Jones
Department of Engineering Science
Oxford University, Parks Road
Oxford, OX1 3PJ, United Kingdom

* Visiting Research Fellow at Warwick University, QinetiQ, Code Technology Park, RM 2041, Bldg A57, Ively Road, Farnborough, Hampshire, G414 0LX, United Kingdom
† School of Engineering, University of Warwick, Coventry, CB4 7AL, United Kingdom

1 Abstract

Heat transfer between the working fluid and the combustion chamber in an internal combustion engine is one of the most important parameters for cycle simulation and analysis. The heat transfer influences the in-cylinder pressure and temperature levels, engine efficiency and exhaust emissions.

Most of the current research carried out on combustion chambers focuses on gas temperature measurement by Coherent Anti-Stokes Raman Scattering (CARS) and heat transfer measurements by thermocouples. Heat transfer measurement by thermocouples leads to poor bandwidths and large uncertainties. A more advanced experimental technique for heat transfer measurement used in gas-turbine engine research, platinum thin film resistance thermometers, has been recently employed in a single cylinder engine. Heat transfer rate measurements have been successfully obtained on the piston surface and cylinder head exposed to the combustion gases. The thin film gauge system has a frequency response of around 100kHz and hence can track the heat transfer rate changes on the piston surface and cylinder head adequately. Measurements taken with the engine motored and at low load are presented and discussed.

2 Introduction

Heat transfer measurements within internal combustion engines has become increasingly important with the drive towards higher efficiencies and cleaner exhaust emissions as well as increased energy levels at the exhaust for turbo-charging. Although internal combustion engines have been studied for many years the combustion chamber temperature and heat transfer rates have been investigated to a lesser extent.

During a combustion cycle the peak gas temperature can reach levels around 2500 K. The metal components of the combustion chamber can withstand approximately 600 K for cast iron and 500 K for aluminium alloys (Lim, 1998). Hence, cooling of the cylinder head, block and piston is required. The heat flux levels experienced in a combustion chamber varies both spatially and periodically and reaches levels as high as several MW/m^2. Indeed this can lead to local regions with high thermal stresses resulting in cracking of the components. Furthermore, lubrication of the cylinder walls is achieved with a film of oil which will deteriorate above approximately 450 K.

Nearly all the reported experimental studies of in-cylinder heat transfer have been carried out with sparsely fitted fast response thermocouples. These record the surface temperature during an engine cycle. The surface temperature is then used to evaluate the surface heat flux.

Alkidas, Puzinauskas and Peterson (1990) took heat flux measurements in the combustion chamber and showed that a significant spatial variation existed in the combustion chamber due to combustion non-uniformities. Myers and Alkidas (1982) showed with their measurements that the magnitude of the initial high heat flux was dependant on the gas pressure and the local burned gas. The spark timing strongly influenced the rise of heat flux and the magnitude of the peak heat flux level. Other studies showed similar results (Hoag (1986), Harigaya, et al. (1990) and Enomoto, et al. (1985)).

Paper presented at the RTO AVT Symposium on "Advanced Flow Management: Part B – Heat Transfer and Cooling in Propulsion and Power Systems", held in Loen, Norway, 7-11 May 2001, and published in RTO-MP-069(I).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **00 MAR 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **High Bandwidth Heat Transfer Measurements in an Internal Combustion Engine Under Low Load an Motored Conditions**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NATO Research and Technology Organisation BP 25, 7 Rue Ancelle, F-92201 Neuilly-Sue-Seine Cedex, France**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Also see ADM001490, presented at RTO Applied Vehicle Technology Panel (AVT) Symposium held in Leon, Norway on 7-11 May 2001, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

This paper describes the use of a new type of heat transfer gauge, which was developed at the Osney Laboratory at Oxford University (Jones, et al. (1988)), to measure heat flux on gas-turbine blades operated at simulated conditions. These have been applied to a spark ignition engine on the piston surface and the cylinder head. The application of these gauges is demonstrated and the measurements are presented and discussed.

3 Experimental Facility and Instrumentation

3.1 Engine configuration

The engine used for this investigation is a single cylinder four stoke Briggs and Stratton, model 92232, type 1245E1. For research purposes a single cylinder engine has certain advantages over multi-cylinder engines such as the inter-cylinder variation can be avoided, fitting instrumentation is easier and the fuel has to be controlled for only one cylinder. The work also forms part of a data fusion study (Bryanston-Cross 1999) which is researching into the application of data processing techniques in complex multidimensional areas such as combustion. The cylinder bore of the test engine is 65mm with a stroke of 44mm and a compression ratio of 6:1. The engine has a cubic capacity of 146 cm^3. The main bearings are oil lubricated and the engine is air cooled.

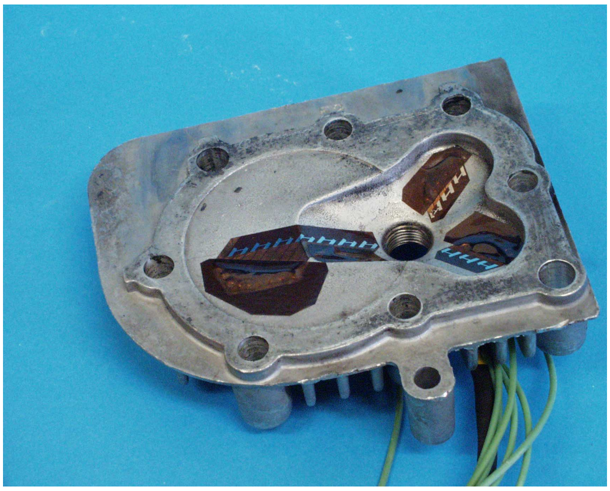

Figure 1a, Cylinder Head instrumented with thin films.

Figure 1b. Piston instrumented with thin films

The manufacturers supplied magneto ignition system was used to provide the ignition spark. The spark discharge was not found to interfere with the heat transfer measurements. The thin film gauges were applied to both the piston surface and the cylinder head as shown in figures 1a and 1b. For the piston, the wires were passed through a hole drilled through the piston crown and passed along the skirt. These wires hung freely and then passed through the sump housing. For the cylinder head, the wires were passed through holes drilled in the head. The engine speed and crank position was measured using a once per rev and a 360 per rev optical shaft encoder.

The engine was operated up to a speed of approximately 3500 rpm. The tests were carried out with an initial motored period and then a fired period. During the motored period the fuel was not allowed to enter the piston chamber, after some cycles of motoring, fuel was initiated and the fired run took place. The ignition system was operational for both the motored and fired period

3.2 Instrumentation

For the heat transfer measurement thin film gauges developed for transient heat transfer measurements on gas turbine blades (Jones, 1993) were used. Thin film sensors have been used on turbine blades at simulated temperatures for around two decades, for transient heat transfer measurements. A further development of these gauges has been reported more recently by Piccini et al. (2000). The gauges are instrumented on to a

flexible plastic sheet (polyimide) 50 μm thickness. Which are easily bonded on to Perspex or metal components.

The thin film gauges are used to evaluate the surface temperature change by supplying a constant current and monitoring the voltage change with the change of resistance with time. A gauge calibration of temperature-resistance gives the temperature history. The frequency response of the heat transfer measurement system is 100 kHz. To monitor the piston and cylinder head metal temperature, fast response K type thermocouples were embedded in the metal surfaces under the plastic layer below the thin film gauges, see Figure 2; thus, the temperature history on both the top and bottom surfaces of the plastic layer may be found and the heat transfer history calculated.

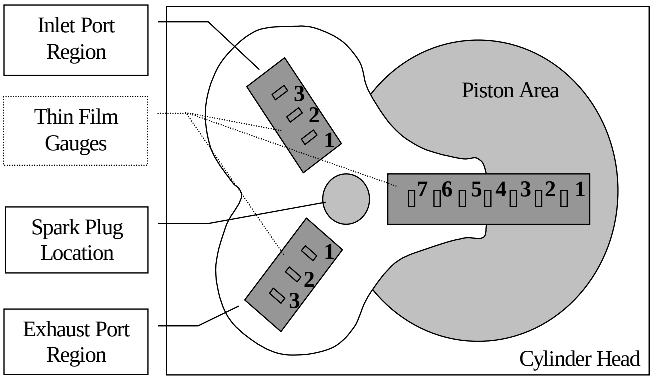

Figure 2, Schematic of instrumentation.

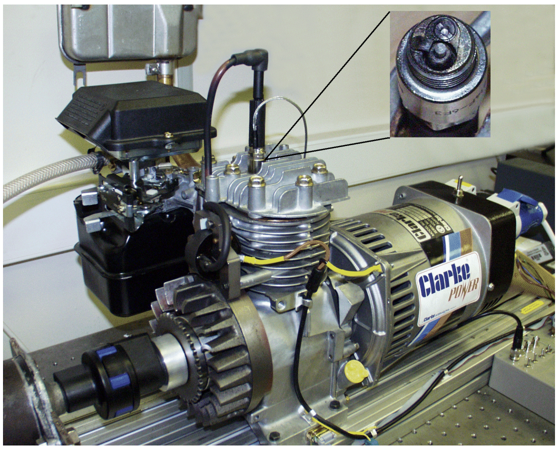

Figure 3, Photograph of test rig (with sparkplug inset showing electrode and transducer).

A standard Kistler sparkplug with an integral pressure transducer was fitted to the engine, Figure 3.

3.3 Recording system

Signals from the thin film gauges, thermocouples, pressure transducer and shaft encoder were recorded on a Data Translation, 8 channel, analogue to digital converter with each channel sampled at 100 kHz and recorded with 300,000 samples per channel. In addition, a 50kHz anti-alias filter was employed.

4 Data processing for heat transfer rate

The recorded voltage from the thin film gauges is first processed to temperature using the temperature resistance calibration. For the evaluation of heat transfer rate the one-dimensional unsteady heat conduction equation has been applied. A single layer model was employed to calculate the heat transfer rate from the surface temperature histories on top and bottom of the plastic layer. For a full description of the processing method see Oldfield et al. (1978), Oldfield (2000).

5 Results and Discussion

The measured surface temperature history from a thin film gauge and a thermocouple from the piston crown are show in figure 4. The data have been taken with the engine motored at 1500 rpm initially and then fired causing it to reach a given speed. The peak surface temperature during the motored run is about 10°C above the ambient temperature and rises to just over 120°C above ambient once the engine is fired. The surface temperature is lower for the initial two revs as the engine speed increases, and then settles at around 100ºC above ambient; however, some fluctuations from cycle to cycle are still noted. The reasons for the initial few cycles having a lower peak temperature are due to the engine being at a lower speed. Notably the minimum cycle temperature is almost constant later in the run at around 40ºC. The thermocouple mounted in the piston below the thin film gauge shows a slow rise of a few degrees as the piston metal temperature rises. Thin film gauges from the cylinder head showed similar data for surface temperature.

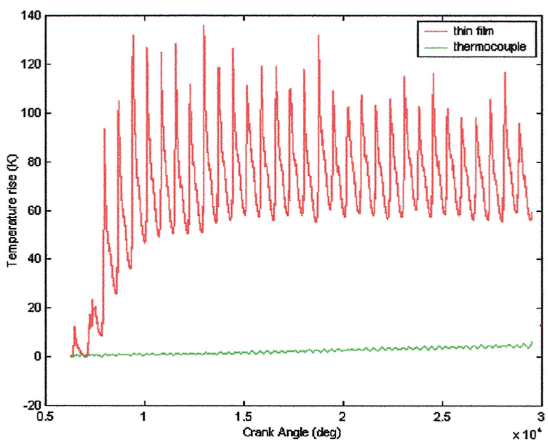

Figure 4, Measured temperatures from the thin film gauge and thermocouple.

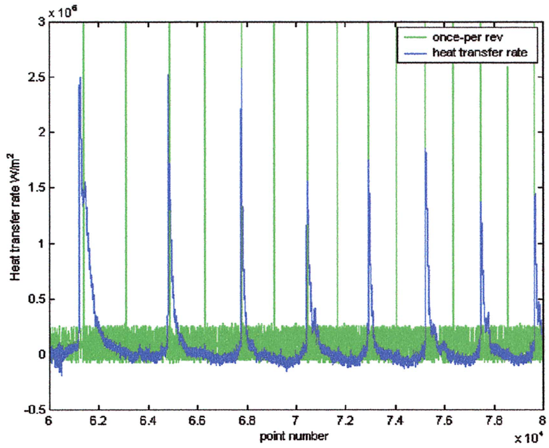

Figure 5, Heat transfer rate from the piston surface for 8 cycles.

Figure 5 shows the heat transfer rate evaluated for a gauge situated at the centre of the piston surface during the fired part of the run, at 3000 rpm, for 8 cycles. The peak heat transfer rate reaches a level of 2.5 MW/m$^{2.}$ The peak heat transfer rate during the motored condition was measured at 0.1 MW/m^2. Notably the peaks coincide with the once per rev signal for every other cycle of the piston as one would expect on the firing stroke. However, a closer look at the data (figure 6 & 7) shows that the peak heat transfer rate occurs shortly after the TDC position. The peak heat transfer level varies significantly from cycle to cycle, whereas the minimum level is about the same. The lower level of heat transfer shows negative values, this is because the ambient air drawn in is at a lower temperature than the piston surface.

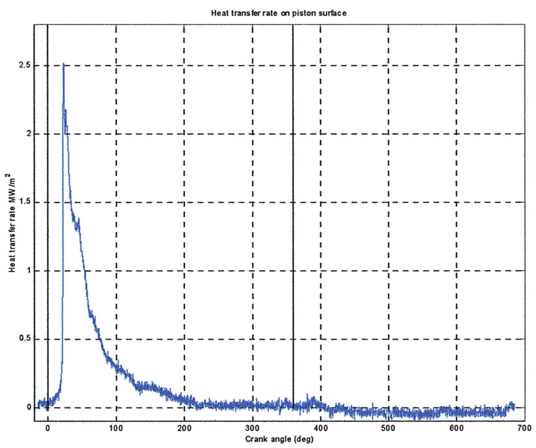

Figure 6, Heat transfer rate for the piston surface for one cycle.

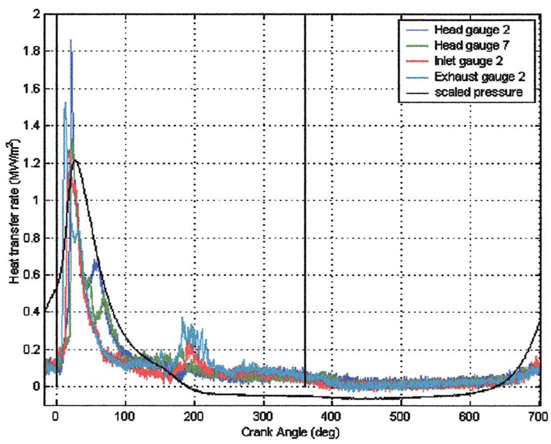

Figure 7, Heat transfer rate from the cylinder head for one cycle at 3000 rpm.

Figure 6 shows the data for one cycle from the piston surface plotted against crank angle. This shows a very sharp rise in heat transfer shortly after the TDC position and then a sharp fall before a small increase and then a further gradual decrease. After about 200º crank angle when the piston has reached the BDC, a further reduction in heat transfer rate is seen, this is due to the exhaust valve opening as the piston moves towards the TDC position again. From the TDC position, once the piston starts to move down, the inlet valve opens drawing in ambient temperature air; this causes a further reduction in temperature as the piston surface is cooled. Then to start the cycle again the heat transfer rate starts to rise as the piston compression is initiated.

For the Cylinder head gauges, the heat transfer rate traces are shown superimposed on one plot in figure 7 with scaled cylinder pressure. Each plot is also given individually in figures 8 to 11. The combustion chamber pressure was measured simultaneously with the heat transfer data. In this case the gauges above the piston area show different features to the gauges near the inlet and exhaust valves. The small differences in time on the sharp rise are caused by the different spatial positions of the gauges and the arrival of the flame front. The inlet and exhaust gauges are the closest to the spark plug which causes them to rise first, gauges in

the piston region are the furthest and hence see a delayed rise. For the two gauges above the piston area a small rise in heat transfer is seen as the piston is moving towards the BDC position after firing. After 180º crank angle when the exhaust valve opens and the piston moves towards TDC the two gauges near the valves show a rise in heat transfer, with the exhaust gauges showing the largest value. A further reduction in heat transfer level is noted after 360º crank angle which is due to the inlet valve opening to allow ambient air for the next compression cycle. Finally, an increase is seen as the compression process starts for the next cycle. The measured combustion chamber pressure shows a peak at the same point in time as the peak heat transfer as expected; however, the width of the pressure peak is much greater than that of the heat transfer data. Measured peak combustion chamber pressure (Figure 13) during the motored run reached 8.5E5 Pa and during the fired part of the run around 2.2E6 Pa. Very little cycle to cycle variation in pressure was noted during the motored part of the run, whereas, the fired run showed significant cyclic variability.

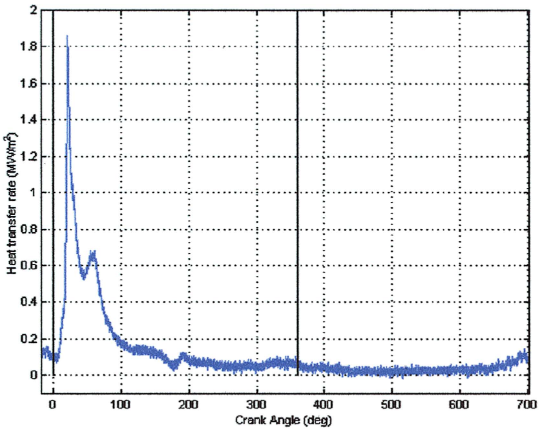

Figure 8, Heat transfer rate for head gauge 2.

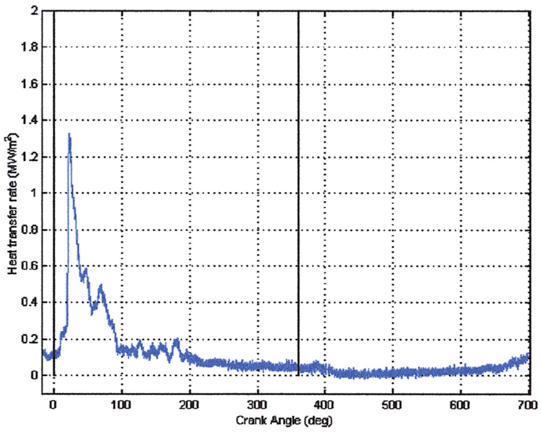

Figure 9, Heat transfer rate for head gauge 7.

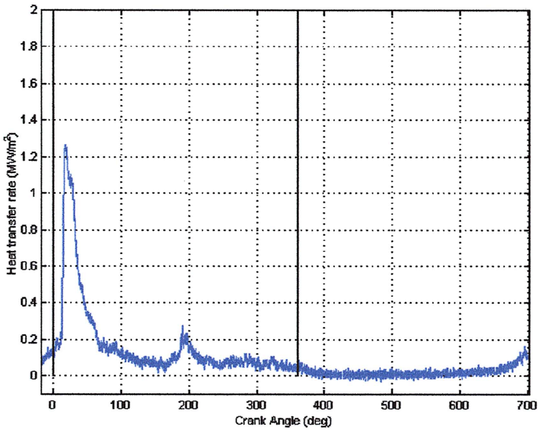

Figure 10, Heat transfer rate for inlet gauge 2.

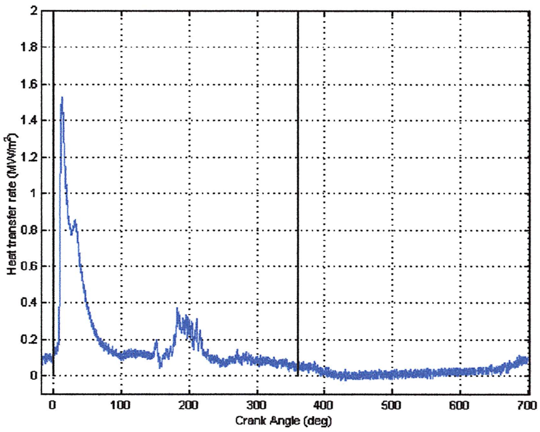

Figure 11, Heat transfer rate for exhaust gauge 2.

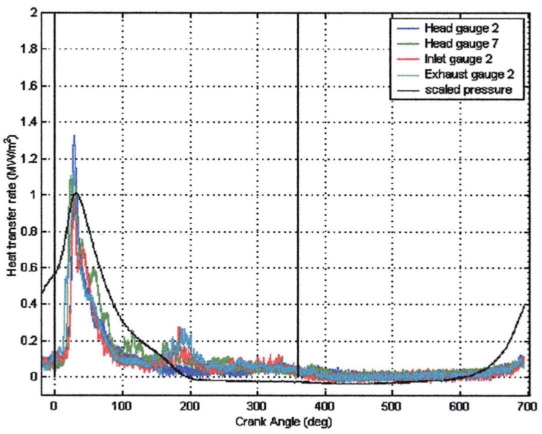

Figure 12, Heat transfer rate for cylinder head gauges at 2000 rpm.

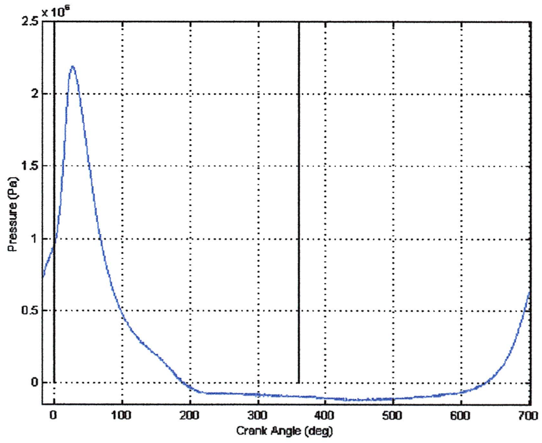

Figure 13, Combustion chamber pressure for one cycle at 3000 rpm.

Figure 12 shows the heat transfer rate measured on the cylinder head for one cycle when the engine was operated at 2000 RPM. Notably the pattern of heat transfer was similar to that at 3000 RPM (Figure 7), however, the heat transfer levels are slightly reduced.

6 Conclusions

Despite the difficulties of instrumenting and obtaining heat transfer on the piston of a spark ignition engine, experimental data has been successfully obtained on both the piston and the cylinder head for a number of positions. The investigation has clearly demonstrated the use of thin film gauges for taking heat transfer measurements in a spark ignition engine operated at realistic conditions.

The peak heat transfer levels found on the piston and cylinder head are of the order of 2.5 MW/m^2 and varied significantly from cycle to cycle. The cylinder head data has shown many structures that can be clearly identified with the combustion process and the engine cycle.

Having proved the application of thin film gauges for measuring heat transfer in spark ignition internal combustion engines, further detailed measurements and analysis can now be carried out for combustion cycle and performance investigations. Furthermore, this technique can now be used as a working diagnostic tool for engine development.

7 Acknowledgements

Thanks to Prof. M L G Oldfield for providing the heat transfer signal processing software, and also to EPSRC and the Intersect FARaDAY Project for funding.

8 References

1. Alkidas, A.C., “Heat Transfer Characteristics of a Spark-Ignition Engine”, Journal of Heat Transfer, Vol. 102 No. 2, 1980.

2. Alkidas, A.C., & Myers, J.P., “Transient Heat Flux Measurements in a Combustion Chamber of a Spark-ignition Engine”, ASME Paper, 1982.

3. Alkidas, A.C., Puzinauskas, P.V. & Peterson, R.C., “Combustion and Heat Transfer Studies in a Spark-Ignited Multivalve Optical Engine”, SAE Paper 900353, 1990

4. Bryanston-Cross, P., Burnett, M., Udrea, D.D., Marsh R., Timmerman, B.H.., Starr, A. & Estabon, J., “The Application of Data Fusion to a Multi Sensored Intelligent Engine.” Invited Paper Presented at: IEE Colloquium on Intelligent and Self-Validating Sensors, 21st June 1999.

5. Enomoto, Y., Furuhama, S., Minakami, K., “ Heat Loss to Combustion Chamber Walls of a 4-Stroke Gasoline Engine”, JSME Paper Vol. 28 No. 238, 1985.

6. Harigaya, Y et al, “Surface Temperature and Wall Heat Flux in a Spark-Ignition Engine Under Knocking Conditions”, SAE Paper 891795, 1989.

7. Hoag, K.L., “Measurements and Analysis of the Effects of Wall Temperatures on Instantaneous Heat Flux”, SAE Paper 860312, 1986

8. Lim, E.P., 1998, Temperature and Heat Flux measurements in a Spark Ignition Engine, Oxford University MSc Thesis.

9. Oldfield, M.L.G., Jones, T.V., Schultz, D.L., 1978, “On-Line Computer for Transient Turbine Cascade Instrumentation”, IEEE Transaction on Aerospace and Electronic Systems, Vol AES-1.

10. Oldfield, M.L.G., 2000, "Guide1 to Impulse Response Heat Transfer Signal Processing: Version 2", OUEL Report 2233/2000.

11. Piccini, E., Guo, S.M., & Jones, T.V., 2000 “The development of a new direct heat flux gauge for heat transfer facility”, Meas. Sci. Techno. Vol 11, 2000, pp 342-349.

12. Jones, T.V., Oldfield, M.L.G., Ainsworth, R.W. and Arts, T., 1993, Transient-Cascade Testing, Chapter 5 of Advanced Methods for Cascade Testing, AGARDOGRAPH 328, AGARD.

Paper Number: 2

Name of Discusser: L. De Luca, Politecnico de Milano

Question:
How do you explain some ....tivaty of your experimental traces?
Can the dynamic response of the sensor be a contributor?

Answer:
The high frequency structure is a real effect from the combustion process, this is proven by the fact that the structure does not exist during the motored part of the run.
The motored and fixed part of run are the same except for the addition of fuel.

Name of Discusser: T. Arts, Von Karman Institute Rhode Saint Genese, Belgium

Question:
Do you have any comment on the “survivability” range of the heat transfer gauges?

Answer:
The gauges have been operated for over 20 runs for many cycles and have survived without any problems.
The only time gauges have been destroyed is if fuel is allowed to enter during the motored period.
This causes excess fuel to collect within the engine, which then ignites suddenly causing a mini explosion.

Name of Discusser: J. Rabiega, Pozman University of Technology, Poland

Question:
How many cycles you mean to be representative?

Answer:
In the case I showed this is not an ensembled mean. It is raw data. The cycle to cycle variation is real and not noise on the signal.
We felt that by doing an ensembled average would not show the cycle to cycle variation.